

Dalitz plot studies in hadronic charm decays

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Recent studies of hadronic D -meson decays are reported. Some experimental searches of CP -symmetry violation using model independent methods are presented. An importance of unitarity constraints in construction of phenomenological models of the D -meson decays is underlined. The theoretical model of the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays, including some two-body unitarity constraints, is described. Then a comparison of the model results with the Belle collaboration data is made. The results on the CP -violation in the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays are given and the necessity to consider the CP -violation in the subsequent K_S^0 decays is emphasized.

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1 Introduction

Studies of the charm meson decays into multimeson final states have many aspects. In particular, one can indicate measurements of the $D^0 - \bar{D}^0$ mixing parameters and the Cabibbo-Kobayashi-Maskawa angle γ (or ϕ_3), and searches of CP violation. Understanding the final state strong interactions between the produced particles, development of the model independent methods or a construction of the models satisfying unitarity, analyticity and chiral symmetry constraints are other important topics. Also improving the isobar models frequently used in analyses of experimental data is highly desirable.

2 Search for CP violation in model independent Dalitz plot analyses

Density distributions of events in the Dalitz plots are studied in three-body D -meson decays. Recently, binned or unbinned methods in searches for CP violation effects in the model independent Dalitz plot analyses are applied. Different variables are used in these studies. For example, in the BABAR collaboration analysis of the $D^\pm \rightarrow K^+ K^- \pi^\pm$ decays [1] the so-called normalized residual variables Δ_i are used

$$\Delta_i = \frac{n_i(D^+) - n_i(D^-)}{\sqrt{\sigma_i^2(D^+) + R^2 \sigma_i^2(D^-)}}, \quad (1)$$

where $n_i(D^+), n_i(D^-)$ are numbers of signal events in the i -th bin of the Dalitz plot, $\sigma_i^2(D^+)$ and $\sigma_i^2(D^-)$ are the statistical uncertainties. The correction factor, $R = \sum n_i(D^+) / \sum n_i(D^-)$, is used to remove the production or detection asymmetries. In the recent publication [2] devoted to the search of the CP violation in the $D^\pm \rightarrow \pi^+ \pi^- \pi^\pm$ decays the LHCb collaboration has used a similar variable S_{CP}^i , called significance:

$$S_{CP}^i = \frac{n_i(D^+) - n_i(D^-)}{\sqrt{R[n_i(D^+) + n_i(D^-)]}}. \quad (2)$$

In absence of CP violation the distributions of the variables Δ_i and S_{CP}^i are standard normal Gaussian functions. In Ref. [2] the LHCb collaboration has also used the unbinned k -nearest neighbour method. In this technique one chooses n_k nearest neighbour events in the combined D^+ and D^- samples with N^+ and N^- events. Then the test variable T is defined as

$$T = \frac{1}{n_k(N^+ + N^-)} \sum_{i=1}^{N^+ + N^-} \sum_{k=1}^{n_k} I(i, k), \quad (3)$$

where $I(i, k) = 1$ if the i -th event and its k -th nearest neighbour have the same D charge and $I(i, k) = 0$ otherwise. In absence of CP asymmetry the T -distribution is Gaussian with known mean and variance values.

Using both binned and unbinned methods the LHCb collaboration has found no evidence for CP violation in the $D^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decays [2]. Also the BABAR collaboration result for the $D^\pm \rightarrow K^+K^-\pi^\pm$ decays was negative [1]. Let us remark here that if the CP violation is not found then there is no model-independent way to find its upper limit. On the other hand, upper limits can be determined in analyses in which a model of decay amplitudes is constructed.

3 Model of the $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays with two-body unitarity constraints

The so-called isobar model is widely used in many experimental analyses of the D -meson decays. However, it is not unitary. Therefore determinations of the branching fractions and the CP asymmetries could not be sufficiently accurate if such a model is applied. In order to improve a description of data an attempt to incorporate two-body unitarity constraints in the model of the $D^0 \rightarrow K_S^0\pi^+\pi^-$ decay amplitudes has been done for the following subchannels: $K_S^0\pi$ S -wave, $\pi\pi$ S -wave and $\pi\pi$ P -wave [3].

A factorization approximation has been used in calculations of the decay amplitudes. The annihilation (via W -exchange) amplitudes have been added to the tree weak decay amplitudes. Strong interactions between the kaon-pion and pion-pion pairs in the S - and P -wave states have been described in terms of the corresponding form factors. The kaon-pion and pion-pion scalar form factors have been constrained using unitarity, analyticity, chiral symmetry and the data on the meson-meson scattering coming from other studies than those on weak decays of heavy mesons. Using these constraints twenty seven nonzero amplitudes have been combined into ten effective independent amplitudes. Some of these amplitudes group several meson-meson resonances. For example, in the pion scalar form factor the three scalar resonances $f_0(500)$, $f_0(980)$ and $f_0(1400)$ are present. Similarly, in the $K\pi$ scalar form factor two strange scalar resonances $K_0^*(800)$ and $K_0^*(1430)$ contribute. This is illustrated in Figure 1. The first maximum of the function seen in the left panel corresponds to the $K_0^*(800)$ resonance and the second one to the $K_0^*(1430)$. Both are of comparable heights.

In the P -wave amplitudes the strange resonances $K^*(892)$ and $K^*(1410)$ are included as well as $\rho(770)$, $\rho(1450)$ and $\omega(782)$. The tensor resonances $K_2^*(1430)$ and $f_2(1270)$ are also present and the corresponding amplitudes are parameterized by the relativistic Breit-Wigner functions. The thirty three free model parameters are fitted to the Belle collaboration data for the $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays [4]. In order to constrain consistently the $K^*(892)$ mass and width the Belle data on the $\tau^- \rightarrow K_S^0\pi^-\nu_\tau$

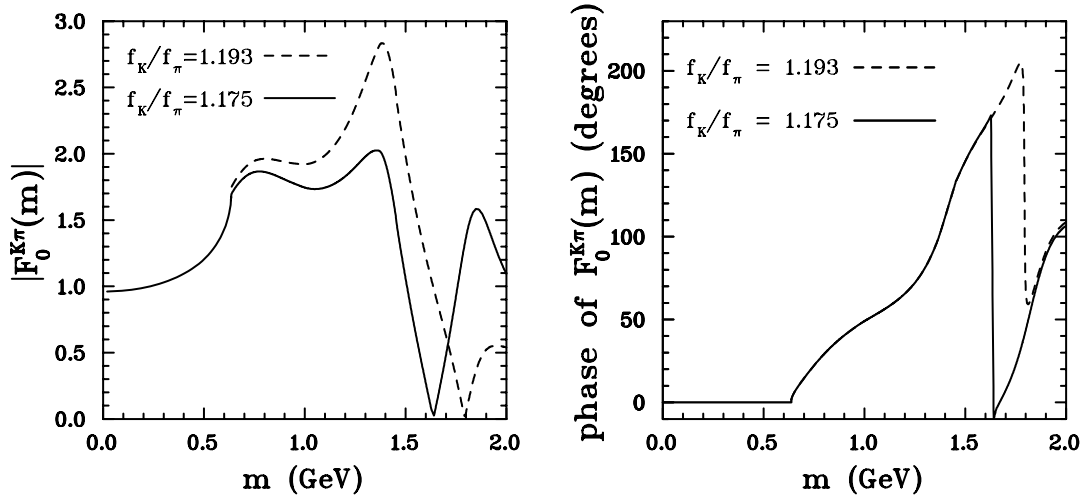


Figure 1: The modulus (left panel) and the phase (right panel) of the $K\pi$ scalar form factor as function of the $K\pi$ effective mass m for two values of the f_K/f_π ratio where f_K and f_π are the kaon and the pion decay constants.

decays [5] have been simultaneously fitted. Also the experimental total branching fraction $Br(D^0 \rightarrow K_S^0 \pi^+ \pi^-) = (2.82 \pm 0.19) \%$ has been included in the χ^2 fit. Let us remind here that in a typical isobar-model application the absolute normalization of amplitudes is arbitrary. The number of degrees of freedom in the fit was $ndf = 6321 + 89 + 1 - 33 = 6378$. The first number, 6321, is equal to the total number of the effective cells covering the Dalitz plot of the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ reaction. The second number, 89, corresponds to the number of bins of the $K_S^0 \pi^-$ effective mass distribution measured in the $\tau^- \rightarrow K_S^0 \pi^- \nu_\tau$ decays. The result of the best fit is $\chi^2 = 9451$ which gives $\chi^2/ndf = 1.48$.

A quality of the fit is shown in Figure 2 where two projections of the experimental Dalitz density distributions are plotted together with theoretical curves.

The resulting parameters and tables of branching fractions for different quasi-two-body channels can be found in Ref. [3]. An important result of the fit is a determination of the lowest values of the branching fractions corresponding to the annihilation amplitudes. These annihilation contributions were found to be relatively large. For example, for the $K_S^0 \pi^-$ S -wave decay amplitude the tree branching fraction is equal to 8.2 % while for the lowest value of the annihilation branching fraction one gets 7.8 %. Both tree and annihilation amplitudes interfere and the resulting branching fraction for this particular channel is equal to 25.0 %.

The theoretical model described above has also been compared with the results of the BABAR collaboration for the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays [6]. This time the model has been fitted to the Dalitz plot density distribution obtained from the isobar model employed by BABAR to parametrize the D^0 decay amplitude. The resulting parameters

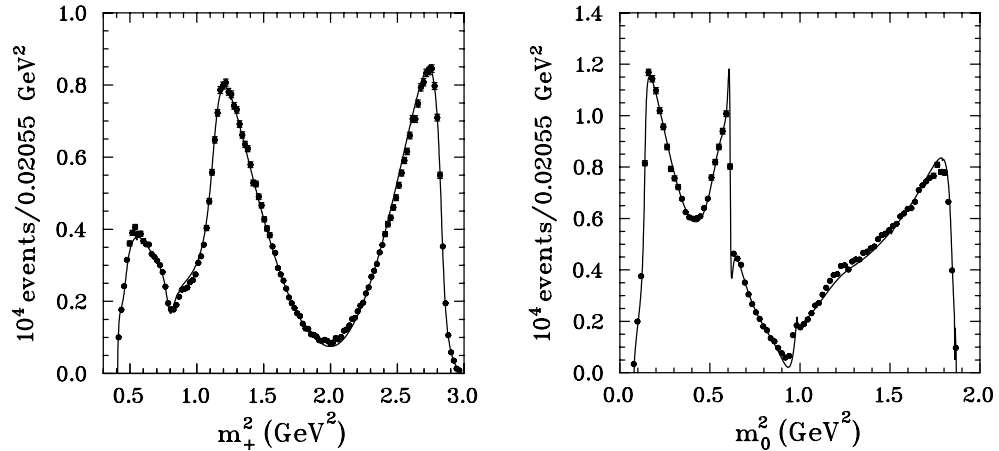


Figure 2: Left panel: comparison of the model $K_S^0\pi^+$ effective mass squared distributions (solid curve) with the Belle data [4]. Right panel: as in the left panel but for the $\pi^+\pi^-$ effective mass squared m_0^2 .

were consistent with those of the previous fit to the Belle data.

4 CP violation in $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays

The CDF collaboration has measured the time-integrated CP -violation asymmetry A_{CP} in the $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays [7]. Using the isobar model to describe the Dalitz plot density distribution the following result has been obtained: $A_{CP} = (-0.05 \pm 0.57 \pm 0.54) \%$, where the first error is statistical and the second one is systematic. This result is consistent with no CP -violation effect and it is consistent with the standard model prediction. The CDF collaboration has also performed a model-independent bin-by-bin comparison of the D^0 and \bar{D}^0 Dalitz plots and again no significant CP violation has been seen.

The Belle collaboration has recently measured the $D^0 - \bar{D}^0$ mixing parameters and searched for the indirect CP symmetry violation in mixing and in the interference between mixing and decay [8]. The results are again consistent with no CP violation.

The CP -asymmetry in the theoretical model described in the previous section is very small, of the order of $5 \cdot 10^{-3} \%$. It is obtained if the CP -violation in the K_S^0 decays is neglected. The above low value is related to the small imaginary part of the Cabibbo-Kobayashi-Maskawa quark matrix element V_{cd} which in the standard model is proportional to λ^5 , λ being the Wolfenstein parameter equal to about 0.225. However, if one takes into account the CP -violation in the K_S^0 decays then the full CP -asymmetry can be estimated to be of the order of -0.3% . This value is comparable to the present experimental uncertainties of the CP violation measurements. Thus

the CP violation effects in K_S^0 decays have to be taken into account in searches for CP asymmetry in the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays.

5 Conclusions

CP violation in D -meson decays has not yet been discovered. In future searches both model-independent and model-dependent methods should be used to study the Dalitz plot distributions of the hadronic charm meson decays. The model-independent methods can be very effective in finding the local CP -asymmetries in different regions of the Dalitz plots. On the other hand, the dynamical models describing the D -meson decay amplitudes have to be further improved by introduction of unitarity, analyticity, chiral symmetry constraints and by inclusion of a hadronic input from studies of other reactions than the weak D -meson decays.

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